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MEASURING CHARACTERISTICS OF THE FASTEST COMMERCIALLY-AVAILABLE DIGITIZERS

J. Kuffel

Measurements of the dynamic performance of eight different digitizers are presented and analysed to show the types and magnitudes of errors to which each digitizer is prone. The impact of these errors on the measurements of fast single shot transients such front-chopped impulses is examined. The suitable range of application of each digitizer is deduced.

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MEASURING CHARACTERISTICS OF THE FASTEST COMMERCIALLY-AVAILABLE DIGITIZERS

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Abstract - Measurements of the dynamic performance of eight different digitizers are presented and analysed to show the types and magnitudes of error to which each digitizer is prone. The impact of these errors on the measurements of fast single-shot transients, such as front chopped impulses with times-to-chopping in the range of 500 ns (the fastest covered by the standards) to a few ns, is examined. The suitable range of application of each digitizer is deduced.

1. INTRODUCTION

The authors' experience in evaluating the fastest available digitizers is presented to aid others in selecting suitable digitizers for recording fast transients such as occur when switching gas-insulated HV apparatus, when measuring Zinc Oxide arrester characteristics, and when testing the compatability of instrumentation to pulsed electromagnetic fields. These fast transients are usually shorter, sometimes much shorter, than the minimum time-to-chopping of 500 ns specified in the relevant measurement standards [1,2]. In the absence of standard specifications we have adopted an arbitrary limit on the maximum error of 10% for both the measurement of crest value and time parameters and use this limit as a guide for establishing the lower limit of the range of application of the digitizers tested in this work. Better accuracy can be attained for impulses at the slower end of the range i.e. durations of a few hundred nanoseconds.

The evaluation of digitizers is an area which has evolved rapidly over the last decade. Early efforts showed the effectiveness of tests using fast triangular waves in characterizing the failure of the analog-to-digital converters (ADC) to keep up with the input signal [3]. However, in the region where the ADC is still performing reasonably well, the superiority of sine wave sources has led to an emphasis on sine wave tests and from this the equivalent bits test has evolved [4,5]. More recently the development of special pulse generators to measure rise times and settling times of digitizers has swung the emphasis back towards ramp tests [6,7]. Important developments have been the related discoveries that the response of a digitizer to a single transient can be quite different from its response to continuous inputs [8] and that the unit step response of a digitizer has two very different time constants [9,10].

The Waveform Measurement and Analysis Committee of the Instrumentation and Measurement Society (IEEE) is preparing a standard which formalizes the testing of digitizers [11]. The draft standard provides information on the tests needed to isolate and characterise all the possible errors in a digitizer. This paper presents a set of tests which will help the power engineer determine the likely bounds on the error in measuring a single-shot transient. Measurements on eight digitizers are presented and analysed to show the types and magnitudes of error to which each digitizer is prone.

It is emphasized that because some of the digitizers were loaned to us for short periods we were not able to make as extensive tests on these digitizers as on those which were available for longer periods.

2. SPECIFICATIONS OF THE TESTED DIGITIZERS

The nominal specifications for each of the digitizers tested in this work are listed in Table 1 and the rms errors for a sine wave are given in Table 2

TABLE 1
NOMINAL SPECIFICATIONS OF DIGITIZERS

Model	Bandwidth (MHz)	Resolution (bits)	Maximum Sampling Rate (MHz)	Record Length (Kbytes)	Type of ADC
A	80[a]	8	200	2	EBS
B	100[a]	8	200	32[b]	Two-stage flash
C	200[a]	9	100 000[c]	0.5	Scan converter
E	100	12[d]	500	4.5	CCD
F	100	6	500	1	Flash
G	20	8	100	4	Parallel flash
H	35	8	100	2	Two-stage flash
K	25	8	100	2	Two-stage flash

Notes:

a. Depends on plug-in used.
b. Expandable to 512 kilobytes.
c. 512 points per sweep, down to 5 ns sweep.
d. For integer data: real data are rounded to 11 bits

TABLE 2
MAXIMUM RMS ERRORS CALCULATED FROM SPECIFICATIONS

Frequency (MHz)	Error for Digitzer (% FSD) A	B	C	H[a]
0.3	0.28	0.32		
0.5		0.32	0.22	
1		0.32	0.28	0.20
5		0.32/0.45	0.35	0.24
10		0.45		0.32
20	0.89	0.45	0.63	0.48
35		0.45		0.84
80	3.54	3.61		

Note a: Measured with half full scale signal.

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(derived from equivalent bits or signal-to-noise specifications). Quantization will produce a maximum possible error of ±½ LSB (lease significant bit = $FSD/2^R$ where R is the resolution in bits and FSD is the full scale deflection) while sampling will produce a maximum possible error equal to the change of the signal in the sampling interval. For a triangular input consisting of a linearly-rising ramp followed by an infinitely fast chop this error would be $\frac{dv}{dt}\Delta t$ where $\frac{dv}{dt}$ is the rate of rise of the input and Δt is the sampling interval (the reciprocal of the sampling rate). In practice the error will be smaller because of the finite rate of collapse of the voltage and because of the response time of the HV measuring system.

The record length must be sufficiently long to allow a complete record of the phenomenon of interest and in this context it should be noted that some of the digitizers allow the sampling rate to be changed allowing a fast transient to be recorded at the maximum sampling rate followed (or possibly preceded) by a slower event recorded at a slower sampling rate. The equivalent bits test gives a measure of how some aspects of the performance degrade with frequency. It is useful for comparing digitizers but is not directly applicable to the estimation of time domain errors. Provided the aperture uncertainty (the variation in the time at which a sample is acquired) and clock instabilities are small compared with the sampling interval these para- meters will not be significant when measuring single- shot fast transients. The rated accuracy gives some indication of what may be expected but does not give any indication of whether better results can be achieved with careful calibration nor of the effect of dynamic errors.

3. PRINCIPLES OF OPERATION OF VERY FAST DIGITIZERS

3.1 Scan Converters

The first attempt at digital recording of short non-repetitive pulses was undertaken in the late 50's in order to enable the on-line processing of the recorded transients. Research in nuclear physics and radar signature analysis prompted the design of a hybrid oscilloscope-TV camera system, which employed a conventional high writing speed CRT coupled to a television vidicon tube scanning the CRT screen. Although very useful in this pioneering period, the hybrid recorder merged the drawbacks of both analog and digital systems. However the concept of fast writing on a temporary storage target and scanning the record at a slower pace was a valuable innovation of the hybrid recorder and paved the road to more refined designs. Digitizers of the second generation (scan converter digitizers) consisted essentially of an analog cathode ray tube with the electron beam writing on a matrix of precharged semiconductor elements. The moving electron beam leaves a trace of discharged elements on the target matrix. The target is then read by another beam scanning the matrix at a slower pace. The slowed down replica of the recorded transient is then digitized by a conventional ADC and stored for further display or processing. When used with additional data processing to reduce the errors caused by blooming (or over-illuminating the target elements) in the slower portion of the recorded transient, scan converters can achieve a vertical resolution of approximately 1% at a sweep of 5 ns. The main errors come from the difference between the electron beam writing speed at the steep and flat portions of the recorded transient, and also from variations in the timebase. Short record length (typically 512) is a limitation of this design. Despite these shortcomings scan converters are used in many laboratories where high bandwidth and very high equivalent sampling rates are needed [12].

3.2 Charge Coupled Devices

Development of the charge coupled device (CCD) formed the base of another type of fast digitizer. The CCD (often called the bucket-brigade circuit) consists of a number of capacitors and electronic switches integrated on a chip and driven by a clock which can operate at fast and slow rates. The first sample of the recorded transient is taken by connecting the first capacitor to the input terminal for a short period. At the next stage the charge accumulated in the first capacitor is transferred to the second one and the first capacitor is discharged in preparation for the next sample. The sampling procedure is repeated at the high rate until the first sample is transferred to the last capacitor. When the recording cycle is completed, the recorded transient is stored in the form of charge accumulated in each capacitor of the CCD. In order to read the signal, the bucket-brigade charge transfer from one capacitor to another is repeated in the reverse direction at the slow rate. The subsequent samples are then digitized by a conventional ADC at the output terminal of the CCD and stored in the memory for further processing.

Digitizer E employs the bucket-brigade principle and has a record length of 4740 words. By using an advanced control system, several MOS integrated circuit registers can be charged sequentially at a maximum rate of 2 ns per sample. Although the output signal from the registers is digitized (at the slower rate) with 12 bit resolution, the gain accuracy of the digitizer is specified as 1%. This limit is set by the analog techniques of sampling the recorded transients with CCD elements.

3.3 Flash Converters

The third type of fast digitizer is based on the conventional flash ADC technique implemented in advanced semiconductor technology. In digitizer B, two monolithic 4 bit flash ADC operating at the maximum sampling rate of 200 MHz each are used in a sub-ranging mode. The input signal is digitized by the first of the 4 bit ADC and the digital output is fed into a digital-to-analog converter (DAC). The output of the DAC is subtracted from the delayed input signal and the residue is fed into the second ADC to give an overall resolution of 8 bits with a quoted aperture uncertainty of 5 ps. Record length, up to 512 kilobytes, is an outstanding feature of this digitizer.

A similar technique is used in digitizers H and K to achieve 8 bit resolution to a 100 MHz sampling rate. Digitizers H and K are from the same manufacturer: digitizer K is an older model which has since been replaced by digitizer H. In digitizer G two 8 bit, 50 MHz flash converters are used to sample the input alternately giving an effective sampling rate of 100 MHz. In this digitizer additional errors may arise from differences in the levels of the two ADC and/or from asymmetry in the sampling intervals. Digitizer F is a 6 bit, 500 MHz flash converter.

3.4 Ribbon-Beam Digitizer

Digitizer A achieves 8 bit resolution at 200 MHz sampling using a unique technique incorporating an electron bombarded semiconductor (EBS) tube. The EBS tube is similar to a cathode ray tube except that the luminescent screen is replaced by an array of diodes and that only one set of plates is used to deflect the ribbon beam. Each of the eight diodes in the target consists of a vertical strip. A metal mask, installed between the electron beam and the diode target, has a pattern of windows cut in it so that the horizontal-ribbon electron beam writes Gray code words on the

target. The input signal deflects the electron beam causing the diodes to switch between the on and off states. The output of each diode is strobed every 5 ns to generate the Gray code word which corresponds to the signal level at the strobing instant.

4. A BLOCK MODEL FOR DIGITIZERS

Fast digitizers of the types described in sections 3.2 to 3.4 can be modelled by an amplifier followed by a noise source, an ideal digitizer, and a block representing non-ideal behaviour of the digitizer (Figure 1). The model amplifier is characterised by the amplitude frequency response, gain, linearity and stability of the digitizer. It is emphasized that all

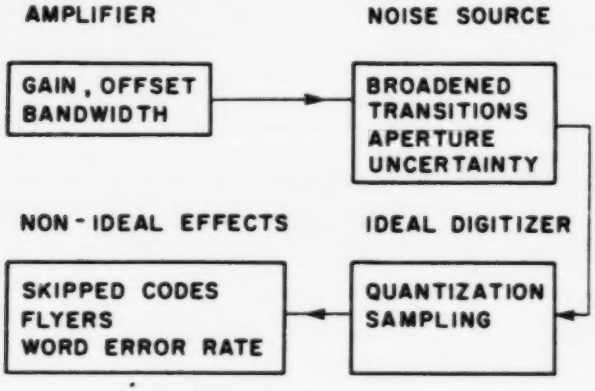

Figure 1: Block Model for Error Sources in a Digitizer

these characteristics are measured by comparison of the record of a test signal to the test signal and represent the characteristics of the complete digitizer. The noise source represents the continuous noise, which broadens the transitions from one level to the next, and the aperture uncertainty, which is treated as an equivalent amplitude error. An ideal digitizer is one whose only errors are quantization and sampling errors. The quantization error has a range of $\pm\frac{1}{2}$ LSB and a standard deviation of $1/\sqrt{12}$ LSB (assuming uniform error distribution). For an input of a sine wave the sampling error will give values of the amplitude which are too small but the size of the error will depend on the phase difference between the signal and the clock of the digitizer. The maximum value $(E)_{max}$ of the sampling error in the amplitude (A) is

$$E_{max} = A(1-\cos\phi)$$

where $\phi = 2\pi f\tau$, f is the frequency of the input, and τ is the sampling period of the digitizer. When the input frequency is so high that there are only four points/cycle, the maximum error is equivalent to 3dB attenuation. Non-ideal behaviour includes errors caused by one or more bits making an arbitrary change or failing to change when they should. There are two distinct types of these errors which occur at very high and very low rates of change of the input signal. Those occurring at very high rates of change of the input are called skip-code errors [3]. Those occurring at very low rates of change are called 'flyers'. When flyers occur as transitions of 1 LSB from their expected value they have been termed 'indecision errors' and a correction procedure has been devised [13]. When they occur as large transitions they can be removed by three-point median filtering. Both these error-correction techniques reduce the effective sampling rate in the region of the error.

This block model is provided as a conceptual aid. Detailed modelling of error sources is outside the scope of this paper.

Systematic errors such as variations from the nominal gain and constant non-linearities should be measured and appropriate corrections applied. Random errors are assumed to be independent and normally distributed and the standard deviation of the overall error is taken as the rms value of the standard deviations of all sources. For practical measurements the maximum error is taken as three times the standard deviation of the overall error. For many digitizers the random error determined from fitting sine waves in the equivalent bits test makes a dominant contribution to the overall error and for these digitizers a '3σ' equivalent bits curve gives a good approximation to the overall behaviour [14].

In this paper scan-converters are treated using the same model even though they are subject to a systematic error caused by the non-linearity of their conventional oscilloscope timebase. Hence this systematic error appears as a random error which makes the scan converters appear worse than they really are: a more appropriate treatment which requires extensive calibration and correction is given in reference [12].

5. DYNAMIC PERFORMANCE TESTS

5.1 Sine Wave Tests

Sine wave testing involves application of a spectrally pure sine signal to the examined digitizer and then fitting a mathematical sine function to the record of digital words obtained at the instrument output. The measurement error is defined as the difference of the values in the digitizer record from the corresponding values of the fitted sine.

Two important considerations in sine wave testing are the purity of the sine wave and the choice of test frequencies. The signal-to-noise ratio of an ideal digitizer is 6R + 1.8 which is 50 dB for an 8 bit digitizer. Allowing a margin of 10 dB sets the requirement that distortion should be less than -60 dB. When this is not available from the generator then filters should be used. For testing a 12 bit digitizer the distortion should be less than -74 dB, or -84 dB when using a 10 dB margin. The measured performance of the generators used in this work are given in Table 3.

TABLE 3
SPECTRAL PURITY OF TEST SOURCES(S)

Source	Highest Harmonic (dBc)
S1U	< -35
S1F	< -55
S1L	< -68
S2	< -44 to < -50
S3	< -54

S1F and S3 were both off-the-shelf generators supplemented with filters. For some of the tests reported here the filters in laboratory 1 were not available and the generator was used without filters (S1U). S2 had a higher harmonic content than is desirable and this may have contributed to the apparent rms error. S1L was an AC calibrator which was used to provide a measure of low frequency performance at 0.1 MHz.

If the test frequency is too close to a sub-harmonic of the clock frequency then only a few levels of the digitizer will occur in the record and the test will not be representative. The test frequency must be sufficiently far from the closest sub-harmonic of the clock frequency that all, or nearly all, the levels between the peak levels may occur in the record. This will be ensured when the period of the greatest common factor of the input frequency and the digitizer's clock frequency is as long, or longer than, the record length [5]. The recorded amplitude should be kept constant when possible because the errors may be dependent on the slew rate for some digitizers.

The variation of the root mean square (rms) value of the measurement error (expressed as a percentage of the nominal FSD) with frequency is shown in Figures 2-5. Figure 2 shows the results for two 8 bit, 200 MHz digitizers together with the rms quantization error, Q8. The letter designations are the same as in Table 2

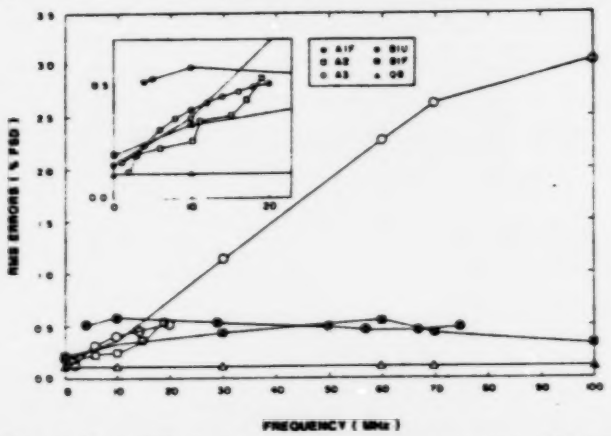

Figure 2: RMS Errors Against Frequency for 200 MHz Digitizers. Curves A1F, A2 and A3 denote three different units of one digitizer tested in different laboratories. Curves B1U and B1F denote different tests on a single unit of another digitizer. The rms error of an ideal 8 bit digitizer is shown for comparison (Q8). Insert detail is the portion of the curves below 20 MHz which has been magnified.

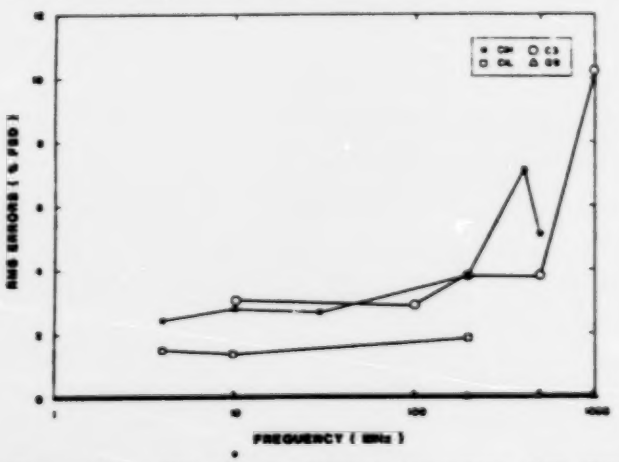

Figure 3: RMS Errors Against Frequency for Scan Converters. Curves C1L and C1H denote the same unit: C1L refers to records with only one cycle of the input displayed on a sweep and C1H refers to records with 3 or more cycles/sweep. Curve C3 denotes tests on a different unit of the same digitizer in another laboratory. The maximum quantization error is shown as Curve Q9.

and the numbers 1, 2 and 3 denote the laboratory in which the digitizer was tested. Figure 3 shows the results for two models of a 9 bit scan converter together with the maximum quantization error (the rms error is too small to be distinguishable from zero). The curve C1L refers to results taken with one cycle displayed on the sweep while C1H and C3 refer to results taken with 3-5 cycles displayed on the sweep. Figure 4 shows the results for two 500 MHz digitizers together with the rms quantization error and the maximum sampling error in the amplitude of a sine wave. Figure 5 shows the results for three 8 bit, 100 MHz digitizers together with the rms quantization error and the maximum sampling error in the amplitude of a sine wave. Low frequency results for C1 have been combined with those in Figure 3 to show more clearly how the rms errors depend on the number of cycles/sweep (Figure 6).

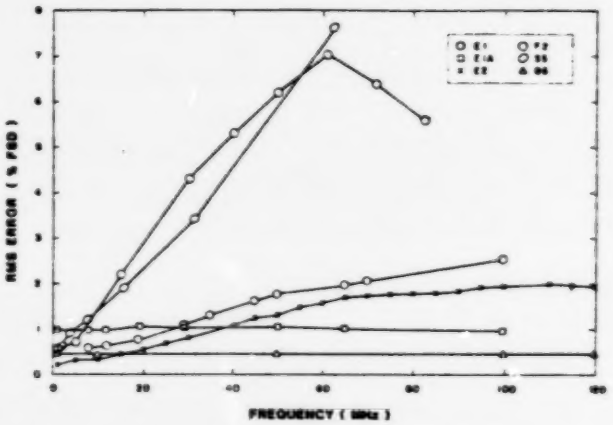

Figure 4: RMS Errors Against Frequency for 500 MHz Digitizers. Curves E1 and E2 denote tests of the same unit in different laboratories. The amplitude frequency response of E1 is denoted by E1A. Curves S5 and Q6 denote the maximum error in amplitude for sampling at 500 MHz and the rms quantization error for a 6 bit digitizer respectively. Curve F2 denotes test results of a 6 bit digitizer.

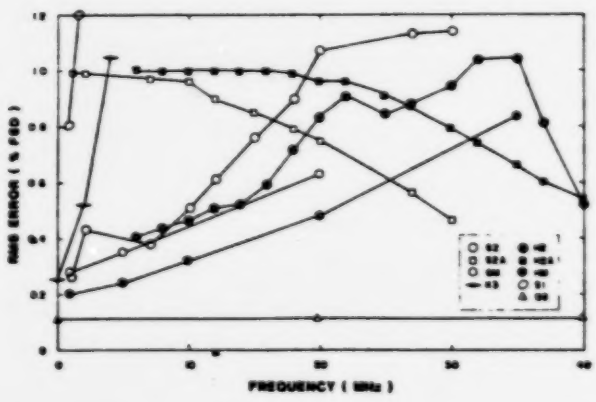

Figure 5: RMS Errors Against Frequency for 100 MHz Digitizers. Curves G2, G2A, and GN denote the test results, amplitude frequency response, and specifications of digitizer G. Curves H2, H2A, and HN denote the test results, amplitude frequency response, and specifications of digitizer H. Curves S1 and Q8 denote the maximum error in amplitude for sampling at 100 MHz and the rms quantization error of an 8 bit digitizer. Curve K3 denotes the test results of digitizer K, the ancestor of digitizer H.

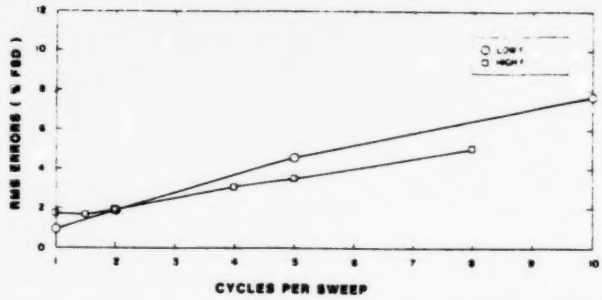

Figure 6: RMS Errors Against Cycles per Sweep for C1. Circles denote measurements taken below 0.1 MHz with SIL. Squares denotes measurements from 10 to 10^3 MHz with SIU.

There is much more information available from sine wave testing than is shown in the rms error curves but the problem is to present it in a condensed fashion which is sufficiently clear to the user. One method is to plot a histogram of the error distributions (Figure 7) and to make a graphic comparison with normal distribution which has been fitted to the error file. The variation of the error distributions with frequency is shown in Figure 8 for four of the tested digitizers. Another method is to make a numeric comparison. For low frequencies all the recorded errors fall inside $\pm 3\sigma$. However as the frequency increases some errors may be greater than 3σ and two parameters which may be used to characterize digitizer behaviour are the number of errors whose magnitudes are greater than 3σ and the normalized range of errors which is defined as the largest magnitude divided by 3σ. Values of these parameters are given in Table 4.

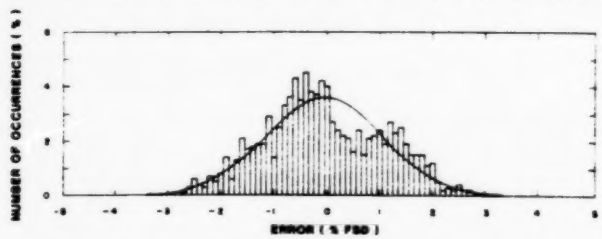

Figure 7: Histogram of Errors (Digitizer E1 at 30 MHz)

Table 4
Nomalized Range (followed by number outside $\pm 3\sigma$)

Unit	Nominal Frequency Per Unit Sampling Rate		
	0.05	0.2	0.5
A1	1.16(4)	1.33(6)	1.65(7)
B1	1.11(3)	1.01(1)	1.13(9)
E2	0.98(0)	0.97(0)	1.04(2)
F2	1.34(23)	1.26(11)	-
G2	1.25(7)	0.99(0)	-
H2	1.09	1.14(5)	1.46(15)
	Cycles/Sweep		
	1	4	10
C1	1.08(2)	0.86(0)	1.28(4)

Frequency dependent attenuation can be measured by taking the amplitude frequency response of the digitizer. Unfortunately amplitude-levelled sources of sine waves to 100 MHz and beyond with sufficient accuracy to fully characterize high resolution digitizers are not readily available. However commonly available sources are adequate to define the limits of the bandwidth and measurements have been made for several digitizers (Figure 4, E1A; Figure 5, G2A and H2A).

5.2 Pulse Tests

5.2.1 The Unit Step Response (USR)

When a step, whose rise time is shorter than the sampling interval of the digitizer, is applied to the digitizer there are two inherent problems. One is the fact that the digitizer will record either one or zero points on the transition. The second is that when a point is recorded on the transition, the value of this point will change from record to record. These variations are caused by the lack of synchronization between the input step and the clock of the digitizer. Even when the input circuits of the digitizer extend the rise time of the input step, there will generally still be only a few points on the transition and these will be subject to variations from one record to

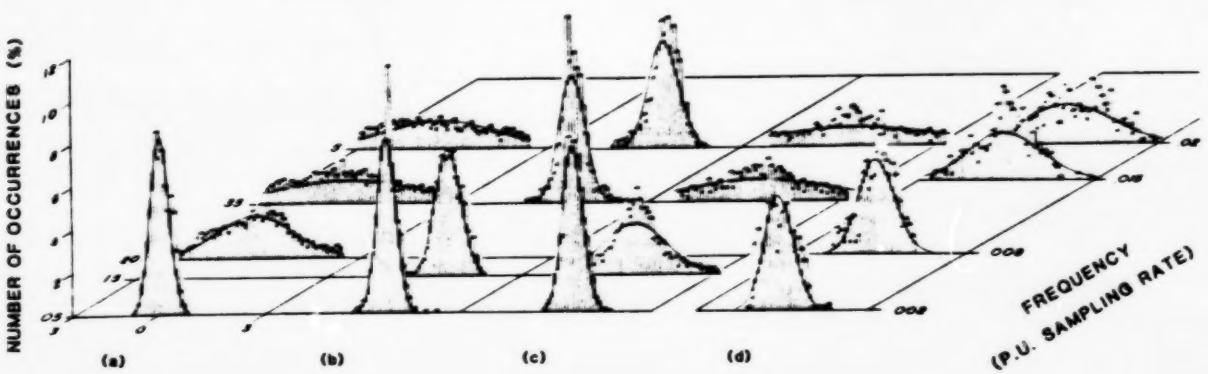

Figure 8: Histograms of Errors - variation with frequency: results for digitizers E2 (a), B1 (b), and A1 (c) are shown for the range 0.15 to 0.5 of the sampling frequency (left hand scale on Z axis) while results for digitizer C1 (d) are shown for the range 0.002 to 0.02 of the sampling frequency (i.e., 1 to 10 cycles/sweep)

another. However such records can still be used to determine whether further tests are worthwhile or whether the digitizer is unsuitable. The unit step response of certain digital recorders has been found to have two time constants: a fast time constant which is a measure of the bandwidth of the digitizer and a very much slower time constant (tens of milliseconds) which is determined by thermal effects within the digitizer [9,10]. Only the fast time constant is of interest for the measurement of fast transients and it should be noted that dc and/or low frequency calibrations are not applicable.

Step responses were taken using a co-axial, mercury-wetted, latching relay which was connected directly to the input connector of the digitizer. The rise time of this step is believed to have been less than 1 ns and this is supported by measurements of the

Table 5
Upper Limits on Response Parameters

Unit	Rise Time (ns)	Settling Time (ns) to 5%	to 3%
A	10	10	15
B	10	10	25
C	1.7	1.9	2.0
E	8	16	44
G	20	20	20
H	10	20	90
K	40	40	140

rise time of digitizer C1 (Table 5 and Figure 9). The measured rise time of 1.7 ns is approximately equal to the expected value of 1.75 ns calculated from the nominal bandwidth of 200 MHz (350/200) and this supports the assumption that the contribution from the rise time of the input pulse is small. The rise time of C1 could be measured accurately because of the very high equivalent sampling rate of this scan converter (100 GHz) which gave 194 samples on the 10% to 90% transition. However all the other digitizers had only a few points on the rise time and so the results are presented as upper limits. This is also true of the settling times given in Table 5. More accurate measurements can be made of the step response of digitizers by using equivalent time techniques but the approximate values given here are sufficiently accurate to decide which digitizers are suitable in particular HV impulse measuring systems. The complete measuring system should then be characterized by its step response using equivalent time techniques if necessary.

5.2.2 Differential Non-Linearity

Differential non-linearity can be measured by using any rapidly changing input whose amplitude distribution is known. In practice either sinusoids [5] or pulses [15] have been used. In this work pulses whose edges were approximately linear have been used. A large number of records have been taken for each pulse rise time and the number of occurrences of each digital level have been counted. The number of occurrences in each level for an input whose rise time is much longer than the sampling interval is shown in Figure 10 (digitizer C1). The profile is approximately flat in the middle and rises to a peak at each edge. These peaks correspond to the top and bottom of the input pulse. For an input whose amplitude distribution is uniform the profile would be horizontal except where it was influenced by the differential non-linearity of the digitizer. If a particular level is wide it would occur a relatively large number of times and stick up, like a chimney, above the surrounding profile. If a level is narrow it would occur a

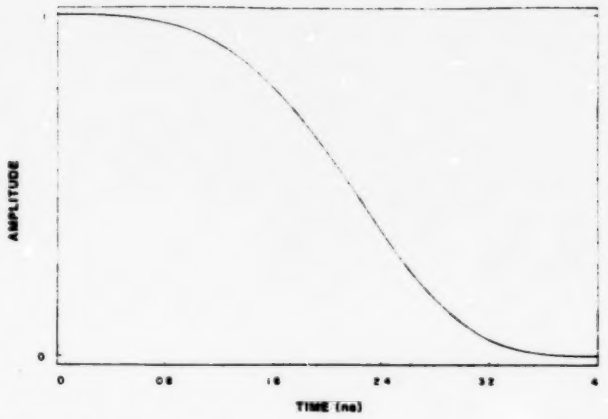

Figure 9: Step Response of C1

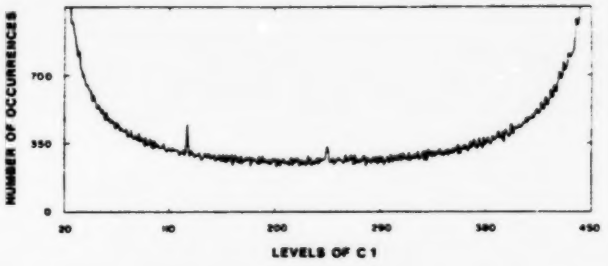

Figure 10: Profile of 700 Step Responses of C1

relatively low number of times and drop down, like a well, below the surrounding profile. The differential non-linearity of the n^{th} level is defined as one less than the quotient of measured probability of occurrence of the n^{th} level and the ideal probability (P_n) of occurrence of the n^{th} level [5]

differential non-linearity = (measured P_n/ideal P_n)-1

The large excursion at level 127 in Figure 10 represents a differential non-linearity of approximately 0.3 LSB or 0.1% FSD. For measurements of fast transients this is a trivial contribution to the expected overall error and only extreme non-linearities where the measured P_n becomes zero for some values of n will be of concern (skip-code errors).

The changes which take place in the centre of this profile as the rise time of the pulse is decreased relative to the sampling interval are shown in Figure 11 and 12 for digitizer A1 and B1 respectively. For A1 as the rise time is decreased the profile becomes more uneven and some levels no longer occur (Figure 11). Rise times of the fastest pulse recorded without missing levels and the fraction of levels occupied for the fastest obtainable rise time are given in Table 6.

Table 6
Rise Time Limits

Unit	Rise Time of Unit U_R (ns)	Fraction Occupied at U_R (%)	Rise Time for All Levels (ns)
A	4.5	20	70
B	3.5	94	>500
C	1.75	100	1.75
E	3.5	100	3.5
H	10	89	-

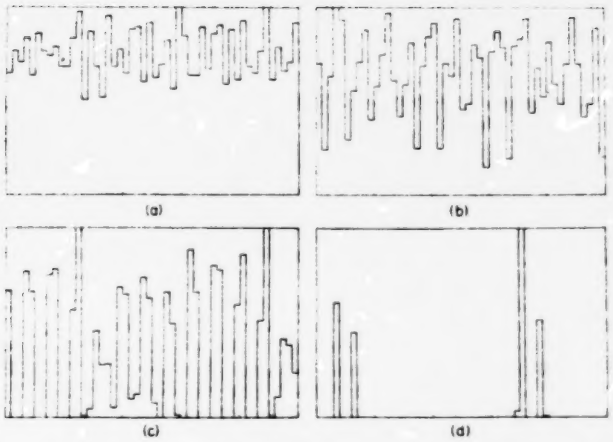

Figure 11: Centres of Profiles for Ramp Tests of A1. The centres of four profiles from level 90 to level 140 are shown for (a) input pulse rise time 500 ns, (b) input pulse rise time 70 ns, (c) input pulse rise time 20 ns, and (d) input pulse rise time 4.5 ns (estimated from digitizer bandwidth).

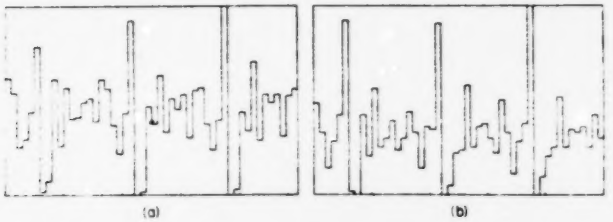

Figure 12: Centres of Profiles for Ramp Tests of B1. The centres of two profiles, from level 90 to level 140, are shown for (a) input pulse rise time 500 ns, and (b) input pulse rise time 3.5 ns (estimated from bandwidth)

6. DISCUSSION

6.1 Sine Wave Tests

In the range up to 20 MHz the results for digitizers A1, A2 and A3 (three different units of the same model) have a maximum vertical spread in the three curves of 0.15% FSD which is considered good for a digitizer whose resolution is 0.4% FSD and whose equivalent ideal digitizer has an rms error of 0.113% FSD. Above 20 MHz the results for A1 show steady growth of the rms error up to the Nyquist frequency of 100 MHz. However, the values obtained are within the specifications (Table 2). Results above 20 MHz were not available for A2 and A3. Digitizer B1 when tested with a source of adequate spectral purity (curve B1F, highest harmonic at <-55 dB) shows similar behaviour at the lower frequencies but at higher frequencies the rms error drops slightly. The values are much lower than for A1 and they are less than the specified rms errors. A further set of results was taken with B1 using a source of inadequate spectral purity (the same source as for curve B1F except the external filters were removed, highest harmonic at <-35 dB) and these results, B1U, lie above B1F at low frequencies. However at higher frequencies the difference is smaller and this is attributed to (1) the larger rms errors above 20 MHz, and (2) the greater attenuation of harmonics of the higher frequencies by the input amplifier used with B1 (nominal bandwidth 100 MHz).

Results for scan converters, C1 and C3, (two different units of the same model) show larger errors. The results from one laboratory showed very large scatter and these are plotted as two families; C1L, the lowest errors and C1H, all other errors. In confirmation of earlier work [16] it was found that the results with lower errors were taken with only one cycle of the input signal/sweep while those with higher errors had 3 or more cycles/sweep. All the results on curve C3 were taken with 3 or more cycles/sweep. Low frequency results for C1 have been combined with those of Figure 3 to show that the rms errors depend on the number of cycles/sweep (Figure 6). This is consistent with the fact that the relative digitizing rate is fixed at 512 samples/sweep. The values of C1L can be taken as an upper limit on what can be achieved at one cycle/sweep with this digitizer because (1) the spectral purity of the source was not good enough for 9 bit digitizers and (2) no correction was made for the systematic errors present in the scan converter (non-linear time base and pin-cushion effect). However the rapid increase in error with the number of cycles/sweep is the dominant effect with this digitizer and this increased error is attributed to (1) blooming near the crest of sinusoids, (2) insufficient writing speed at zero crossings leading to automatic linear interpolation, and (3) possible problems in the estimation of frequency by the fitting algorithm caused by the non-linear timebase and exacerbated by the greater number of zero crossings.

No signal sources of the very high purity needed to test the 12 bit digitizer E (E1 and E2 refer to tests on the same unit at different laboratories) were available. Source S1 was used to test E1 and source S2 was used to test E2. The highest harmonic on S2 ranged from <44 dB at 5 MHz down to <50 dB at 70 MHz and at 1 MHz. In addition although the amplitude was the same at low frequencies for tests of both E1 and E2 a lower amplitude (by 15% at 100 MHz) was used at the higher frequencies for tests on E2. Tests on E1 showed that a 30% drop in amplitude at 100 MHz produced a 50% drop in the rms error. At low frequencies the curve for E1 was below that for E2 because of the higher spectral purity of S2. At higher frequencies the relative purity of S2 increased and there was a drop in amplitude for tests on E2. These two factors have maintained the difference in curves E1 and E2. Further tests were made on E1 at dc and at low frequency. Calibration of various dc levels using a power supply whose noise was small compared with 1 LSB showed that the dc records were contaminated by noise with an rms value of 0.13% FSD. Tests with S1L up to 0.1 MHz gave rms errors of 0.2% FSD. The value of 0.19% FSD measured at 1.1 MHz on E2 suggests that spectral impurities of this source (<50 dB) are not contributing as much as might have been expected to the rms errors. This is because internal noise has reduced the performance of the 12 bit digitizer to the equivalent of 7 bits for which S2 is adequate but S1 is not. Tests on F2 showed comparatively large errors which increased up to 50 MHz and then decreased. Although no measurements with different amplitudes at the same frequency were made on F2, a 25% drop in amplitude at high frequency during the tests likely caused the apparent drop in rms error (judging from measurements on other digitizers). Also shown in Figure 4 is the maximum sampling error (S5) in the amplitude of a sinusoid for 500 MHz sampling. This is the error which can occur in the single shot measurement of a single cycle of a sine wave and serves to emphasize that the rms errors taken over many points give values which are extremely low compared with the errors which can occur in single shot recording.

The results for G2 and H2 are quite close at low frequencies but the errors for G2 are higher by up to 0.3% FSD around 25 MHz. Both these digitizers were tested with an amplitude-levelled input rather than constant recorded amplitude and their amplitude frequency responses are shown as G2A and H2A. It is interesting to see how the errors in G2 are only partly limited by the reduced amplitude signal passed by the internal filter on the input while the errors for H2 are reduced dramatically indicating that the performance of H2 is likely limited by slew-rate dependent errors. The specified S/N ratios have translated to rms errors and are shown as GM (full amplitude signal) and HM (half-amplitude signal). The errors in an older version of digitizer H are shown as K3 and S1 is the maximum sampling error of the crest of a sinusoid for a 100 MHz sampling rate. The measured rms errors for G2 were reasonably close to the specified (GM) for frequencies below 10 MHz. However by 20 MHz the measured errors were higher by a factor of two. For digitizer H the comparison cannot be made since the measured values pertain to amplitudes close to full scale while the specified values pertain to half scale amplitudes. However the difference in H2 and HM is consistent with the difference in amplitudes. The errors in an older version of digitizer H are shown as K3 and S1 is the maximum sampling error of the crest of a sinusoid for a 100 MHz sampling rate.

The relative behaviour of four of the digitizers tested (E2, B1, A1 and C1) is shown dramatically in Figure 8. The first three digitizers have essentially the same error distributions at a frequency of 0.05 times the maximum sampling frequency as C1 has at 1 cycle/sweep (0.002 p.u. sampling frequency). However the performances of E2 and A1 deteriorate rapidly as is shown by the widening of the error distribution as the input frequency is increased. A similar but not so drastic deterioration is observed for C1 but it should be noted that the frequency range (in terms of the effective sampling rate) is much lower for C1. Digitizer B1 shows very little deterioration right up to the Nyquist frequency. The parameters listed in Table 4 show qualitative agreement with Figures 2-5 but more work is needed to establish their value as suitable criteria for acceptance of a unit under test. In particular it is necessary to establish the minimum number of samples which will give a result sufficiently close to the asymptotic value.

6.2 Pulse Tests

Although the rise times and settling times given in Table 5 are only approximate, they show that these digitizers can be used to record very short impulses. The limit on the length of the shortest pulse which can be measured is set by the sampling rate rather than the response characteristics of the digitizer with only one exception, digitizer C. Digitizer C can be used for chopped impulses down to the limits set by the 1.7 ns rise time. For the other digitizers the minimum time-to-chopping which can be measured is ten times the sample interval although at least twenty times is suggested to allow for other sources of error.

The ramp tests on digitizers A1 and B1 show similar results to previously published results on digitizer K [3] and A2 [15]. For digitizer A1 all levels are occupied at rise times of 500 ns down to 70 ns. However by 70 ns the distribution has become very distorted and one level in four has a very low number of occurrences. By 20 ns two adjacent levels in every four have zero occurrences and the maximum possible quantization error of A1 has increased to 1.5 LSB from 0.5 LSB. This behaviour is consistent with the low rms errors measured below 20 MHz and the increasing errors measured above 20 MHz (Figure 2). The increased quantization error is small compared with the sampling error which is 25% for a 20 ns impulse. The behaviour of B1 is quite different because even for a 500 ns rise time there are some levels with zero occurrences. However as the rise time of the input is decreased to 1 ns the profile of occurrences stays nearly the same. This is consistent with (1) the relatively large error of B1 compared with A1 at low frequencies and (2) with the approximately constant error of B1 at high frequencies. Further examination of the empty levels and the associated chimneys in the profiles for B1 show that this problem is associated with the fifth bit of the digital word, i.e., the least significant bit of the more significant 4 bit ADC. This is a potentially more serious problem than occurs with A as it could lead to large errors in ramp measurements. However scrutiny of the individual records used to calculate the profiles of B1 shows that (1) for very fast rise times no flyers are observed, (2) for slower rise times (500 ns) a few flyers are observed, (3) for slowly charging pulses (e.g., on the tail of a standard impulse) they appear regularly with a probability of occurrence of approximately 10^{-4}, and (4) when they occur they are never more than one sample wide. Further work is needed to determine the probability of occurence and how it varies with the slew rate of the input.

Ramp tests on C1 showed virtually no degradation of the occurrence profiles down to input pulse rise times of 1.7 ns. Digitizer E showed some degradation with the decreasing rise time of the input but even at a rise time of about 3.5 ns there were no levels with zero occurrences. Digitizer H2 has been tested only at the fastest rise time of which it is capable (10 ns) and it was found to have an uneven distribution with 11% of the tested levels empty.

6.3 Application to Impulse Tests

The sine wave tests provide a clear characterization of digitizers which is useful in defining their frequency domain characteristics and in making comparative measurements either of two digitizers or of one digitizer at different times. However these frequency characteristics can not be easily transformed to the time domain. Monte Carlo calculations could be made to estimate the likelihood of particular errors in the time domain for a given input but such calculations are complex and time consuming. The estimation of the possible error in a measured record is even more difficult especially when the record is contaminated with noise of relatively large amplitude.

Errors measured in the time domain are directly applicable to the measurement of front chopped impulses. Ideally the ramp test should be made with a low voltage, single-shot ramp whose shape is similar to the impulse to be measured. However if the sampling rate is high enough and the impulse is sufficiently smooth the errors can be estimated by approximating the impulse by sections of various rise times whose errors are known [17].

Whichever set of tests is used to characterise the continuous wave behaviour of a digitizer it is essential to make a direct measurement of the response to a single transient. The USR taken using a mercury-wetted reed relay has been found to provide a convenient and inexpensive method of characterising the single-shot response of digitizers.

7. CONCLUSIONS AND FURTHER WORK

This work shows that scan converters are presently the only digitizers which can be used to measure single transients accurately down to a few tens of nanoseconds duration and the model tested in this work can be used down to a few nanoseconds duration.

Some other digitizers, which are suitable for the measurement of the standard impulses, can be used to measure front-chopped impulses down to times-to-chopping of from 500 ns to in the range of 100 to 20 ns (depending on sampling rate) with a gradually increasing uncertainty which is determined mainly by sampling errors.

Special features of certain models make them more suitable for particular measurements. Digitizer E, which is based on analog sampling in CCD, has the next widest range to C and has the advantage on nearly ten times the record length. Digitizers A and B are useful down to 200 ns and usable to 50 ns. Digitizer A has a timebase that can be switched up to 12 times without losing track and so many short transients at widely separated intervals could be recorded. Digitizer B can be configured with a long enough record that a 2.5 ms interval can be recorded at 5 ns time resolution.

Direct testing of digitizers has shown that time domain measurements are more easily applied to defining the errors in impulse measurements. Differential non-linearity must be measured because it reveals errors which are not shown explicitly by other tests.

This work is being continued to devise and identify standard tests and test sources to simplify the testing of digitizers to qualify them for impulse measurements.

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